

PREDICTION OF SUPERSOFT X-RAY PHASE, HELIUM ENRICHMENT, AND TURN-OFF TIME IN RECURRENT NOVA CI AQUILAE 2000 OUTBURST

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ABSTRACT

Recurrent nova CI Aquilae is still bright 300 days after the optical maximum, showing the slowest evolution among recurrent novae. We predict the turn-off time of CI Aql 2000 outburst coming in August 2001 after a supersoft X-ray source (SSS) phase lasts 250 days. We also predict helium enrichment of ejecta, $\text{He}/\text{H} \sim 0.25$ by number. Observational confirmations are urgently required. Based on the optically thick wind mass-loss theory of the thermonuclear runaway model, we have also estimated the WD mass to be $M_{\text{WD}} = 1.2 \pm 0.05 M_{\odot}$ by fitting our theoretical light curves with the 1917 and 2000 outbursts. The mass of the hydrogen-rich envelope on the WD is also estimated to be $\Delta M \sim 6 \times 10^{-6} M_{\odot}$ at the optical maximum, indicating an average mass accretion rate of $\dot{M}_{\text{acc}} \sim 0.7 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ during the quiescent phase between the 1917 and 2000 outbursts. Using these obtained values, we have consistently reproduced the light curve in quiescence as well as the two outburst phases. Thus, we predict the turn-off time to be in August 2001 for the 2000 outburst. We strongly recommend soft X-ray observations to detect SSS until August 2001 because the massive wind phase have already ended in December 2000 followed by an SSS phase that very likely lasts until August 2001.

Subject headings: binaries: close — novae, cataclysmic variables — stars: individual (CI Aql) — stars: winds, outflows — X-rays: stars

1. INTRODUCTION

The second recorded outburst of CI Aquilae was discovered in April 2000 by Takamizawa (2000) since the first recorded outburst in 1917 (Reinmuth 1925; Duerbeck 1987). Thus, CI Aql has been recognized as a member of the recurrent novae (Yamaoka, Ayani, & Shirakami 2000). After optical brightness reached its maximum $V \sim 9$ in early May 2000, it rapidly decreased to $V \sim 13$ in about 50 days. A plateau phase follows; the brightness levelled off at $V \sim 13.5$. CI Aql is still as bright as $V \sim 14$ until now about 300 days after maximum, being the longest record of on-time among the recurrent novae (e.g., VSNET archives, <http://www.kusastro.kyoto-u.ac.jp/vsnet/>).

Recurrent novae constitute a small class of cataclysmic variables, the outbursts of which repeat in a decade to a century. Ejecta of the recurrent novae are not metal-enriched but similar to the solar value ($Z \sim 0.02$), indicating that the WDs in the recurrent novae are not eroded but have grown in mass (e.g., Starrfield, Sparks, & Truran 1985). Masses of white dwarfs (WDs) in the recurrent novae are estimated to be so massive as the Chandrasekhar mass limit from the light curve fitting (e.g., Hachisu & Kato 1999; Hachisu et al. 2000a; Hachisu & Kato 2000a,b, 2001). These features strongly suggest that the recurrent novae are an immediate progenitor of Type Ia supernovae (SNe Ia) if the WD consists of carbon and oxygen (Nomoto, Thielemann, & Yokoi 1984). Evolutionary paths to SNe Ia via recurrent novae have been

pointed out by Hachisu, Kato, & Nomoto (1999a).

Recurrent novae are divided into three subclasses depending on their orbital periods: T Pyx subclass with a dwarf companion, U Sco subclass with a slightly evolved main-sequence (MS) or subgiant companion, and RS Oph subclass with a red giant companion (e.g., Warner 1995). CI Aql has an orbital period of 0.618 days, belonging to the U Sco subclass. It is therefore likely that the light curve of CI Aql develops like U Sco.

The 1999 outburst of U Sco was densely observed from the rising phase to the final decay phase through the mid-plateau phase. The detection of supersoft X-rays during the plateau phase (Kahabka et al. 1999) strongly supports the theoretical description of nova outbursts — massive wind phase, steady hydrogen burning phase (no winds), and final cooling phase, — which corresponds to the rapid decline, plateau, and final decline phases in the light curve (e.g., Hachisu et al. 2000a), respectively. Because the development of CI Aql outbursts is much slower than that of U Sco, there is still a chance to observe supersoft X-rays. Supersoft X-rays are direct evidence of hydrogen shell burning on a WD so that they provide us valuable information on recurrent novae and SN Ia progenitors.

In this *Letter*, we determine the mass and the growth rate of the WD as accurately as possible by theoretically analyzing light curves. Then, (1) we predict the turn-off time of nuclear burning and the duration of supersoft X-ray source (SSS) phase of the present outburst and (2) examine the possibility whether or not CI Aql will explode

as an SN Ia. In §2, we describe our model of CI Aql in quiescence and estimate the inclination angle, the size and thickness of the accretion disk, and so on. In §3, the 1917 outburst is numerically analyzed and we determine the mass of the WD. In §4, the 2000 outburst is also numerically analyzed and the duration of wind is estimated. In §5, we predict the duration of the SSS phase. Discussion follows in §6.

2. BASIC MODEL IN QUIESCENCE

CI Aql is an eclipsing binary. We have considered a binary model as illustrated in Figure 1 which consists of (1) the WD photosphere, (2) the MS photosphere which fills its Roche lobe, and (3) the accretion disk (ACDK). We assume that the size and thickness of the ACDK are given by two parameters, α and β , as

$$R_{\text{disk}} = \alpha R_1^*, \quad (1)$$

and

$$h = \beta R_{\text{disk}} \left(\frac{\varpi}{R_{\text{disk}}} \right)^\nu, \quad (2)$$

where R_{disk} is the outer edge of the ACDK, R_1^* the effective radius of the inner critical Roche lobe for the WD component, and h the height of the surface from the equatorial plane, ϖ the distance on the equatorial plane from the center of the WD. Here, we adopt ϖ -square law ($\nu = 2$) to mimic the effect of flaring-up at the rim of the ACDK (e.g., Schandl, Meyer-Hofmeister, & Meyer 1997).

The accretion luminosity of the WD (e.g., Starrfield, Sparks, & Shaviv 1988), the viscous luminosity of the ACDK, and the irradiations by the WD (e.g., Schandl et al. 1997) are also included. Here, we assume that the surfaces of the MS and of the ACDK emit photons as a black-body at a local temperature of each surface patch area (see Fig. 1) which is heated by radiation from the WD. The efficiencies of irradiation of the MS and of the ACDK are assumed to be $\eta_{\text{MS}} = 0.5$ and $\eta_{\text{DK}} = 0.5$, respectively. The numerical method is essentially the same as that in Hachisu et al. (2000b) and fully described in Hachisu & Kato (2001). A circular orbit is assumed. Light curves of CI Aql in quiescence has been obtained by Mennickent & Honeycutt (1995). They determined the orbital period and ephemeris to be JD 2,448,412.167(25) + 0.618355 $\times E$ at eclipse minima.

Figure 2 shows the averaged (smoothed) observational points (open circles) together with our calculated V light curves for the suggested WD mass of $M_{\text{WD}} = 1.2 M_\odot$ ($R_{\text{WD}} = 0.0072 R_\odot$) and mass accretion rate of $\dot{M}_{\text{acc}} \sim 1 \times 10^{-7} M_\odot \text{ yr}^{-1}$ (see the following sections). To fit our theoretical light curves with the observational points, we have calculated V light curves by changing the parameters of $\alpha = 0.5$ –1.0 by 0.1 step, $\beta = 0.05$ –0.50 by 0.05 step, $T_{\text{ph,MS}} = 5000$ –8000 K by 100 K step, $T_{\text{ph,disk}} = 3000$ –6000 K by 500 K step, and $i = 70$ –90° by 1° step and seek for the best-fit model by minimizing RMS of the residuals. The light curves are also calculated for four companion masses of $M_{\text{MS}} = 0.8, 1.1, 1.5$ and $2.0 M_\odot$. Since we obtain similar light curves for all of these four cases, we adopt $M_{\text{MS}} = 1.5 M_\odot$ because the mass transfer is as high as $\sim 1 \times 10^{-7} M_\odot \text{ yr}^{-1}$ and this indicates a thermally unstable mass transfer (van den Heuvel et al. 1992), which requires $M_{\text{MS}}/M_{\text{WD}} \gtrsim 1.1$ (Webbink 1985). A $1.5 M_\odot$ MS

expands to fill the Roche lobe of $\sim 1.7 R_\odot$ after a large part of hydrogen at the center is consumed (e.g., Hachisu et al. 1999b).

In the best-fit model, a rather blue color index of $(B - V)_c \approx 0.14$ is obtained as shown in Figure 3. This suggests a large color excess of $E(B - V) = (B - V)_o - (B - V)_c \approx 0.86$ with the observed color of $(B - V)_o \sim 1.0$ (Mennickent & Honeycutt 1995). This color excess is very consistent with $E(B - V) = 0.85$ estimated by Kiss et al. (2001).

3. THE 1917 OUTBURST

First we reproduce the light curve of the 1917 outburst. Its Tycho B magnitude light curve has recently been reported by Williams (2000), which is shown in Figure 4 together with our calculated B light curves. Our numerical method for calculating light curves is fully described in Hachisu & Kato (2001).

It has been established that the WD photosphere expands to a giant size at the optical maximum in nova outbursts. Since the separation of CI Aql is $a \sim 4 R_\odot$ (Greiner & Alcalá 1996), the WD envelope engulfs the MS companion so that the early phase light curve is calculated only from the WD photosphere (e.g., Kato & Hachisu 1994; Kato 1999). The accretion disk and the companion do not contribute to the B light until it decreases to $B \sim 13$ mag. We determine the WD mass to be $M_{\text{WD}} = 1.2 \pm 0.05 M_\odot$ from the early phase light curve as seen in Figure 4.

Assuming $M_{\text{WD}} = 1.2 M_\odot$, we estimate the envelope mass at the optical maximum to be $\Delta M = 5.8 \times 10^{-6} M_\odot$ for the hydrogen content $X = 0.7$. If the duration of quiescence before the 1917 outburst is almost the same as the quiescent phase between the 1917 and 2000 outburst, this envelope mass indicates a mass accretion rate of $\dot{M}_{\text{acc}} \sim 0.7 \times 10^{-7} M_\odot \text{ yr}^{-1}$ if no WD matter has been dredged up. In our wind model, about 81% ($4.7 \times 10^{-6} M_\odot$) of the envelope mass has been blown in the wind while the residual 19% ($1.1 \times 10^{-6} M_\odot$) has been left and added to the helium layer of the WD. The net mass-increasing rate of the WD is $\dot{M}_{\text{He}} = 0.13 \times 10^{-7} M_\odot \text{ yr}^{-1}$. Thus, CI Aql may become an SN Ia if the donor is massive enough.

4. THE 2000 OUTBURST

CI Aql bursted in April 2000. Its optical maximum ($V \sim 9$ mag) was reached on May 5, 2000 (HJD 2451669.5, Kiss et al. 2001). As shown in Figure 5, the visual brightness quickly decreased to 13.5 mag in about 60 days. Then, it stays at $V \sim 14$ mag, i.e., a plateau phase. This mid-plateau phase is very similar to that of U Sco and can also be explained by the irradiation of the accretion disk (Hachisu et al. 2000a). Therefore, we have reproduced the light curve in the plateau phase by assuming similar model parameters to those of U Sco. Theoretical light curves in Figure 5 are calculated for a pair of $1.2 M_\odot$ WD + $1.5 M_\odot$ MS. In the plateau phase of the light curve, i.e., when the WD photosphere becomes much smaller than the binary size, the light curve is determined mainly by the irradiations of the ACDK and of the MS. The unheated surface temperatures are fixed to be $T_{\text{ph,MS}} = 6300$ K for the MS and to be $T_{\text{ph,disk}} = 5300$ K at the disk rim, which are the same as the basic model in quiescence.

The luminosity of the accretion disk depends on both the thickness β and the size α . We have examined a total of 160 cases for the set of (α, β) , which is the product of 16 cases of $\alpha = 0.5$ – 2.0 by 0.1 step and 10 cases of $\beta = 0.05$ – 0.50 by 0.05 step. Here, we have adopted a set of $\alpha = 1.4$ and $\beta = 0.2$ during the wind phase and a set of $\alpha = 0.7$ and $\beta = 0.2$ after the wind stopped.

The decline of the early phase ($t \sim 0$ – 70 days) hardly depends on the hydrogen content X of the WD envelope but the ends of the wind phase and of the hydrogen shell-burning phase depend sensitively on the hydrogen content X as shown in Figure 5. Matsumoto & Kato (2000) reported a sharp ~ 1 mag drop of R magnitude in late November 2000 and Kiyota (VSNET archives) also observed a ~ 1.5 mag drop of I magnitude as shown in Figure 5. If we attribute this drop to the end of wind phase, the hydrogen content is somewhere between $X = 0.35$ and $X = 0.5$, more closer to $X = 0.5$. We here adopt $X = 0.5$. In the case of $X = 0.5$, the continuous wind stopped in early December 2000 about 220 days after maximum and the steady hydrogen shell-burning will end in early August 2001 about 450 days after maximum as shown in Figure 5.

5. SUPERSOFT X-RAY SOURCE PHASE

We here strongly encourage X-ray observations until the mid August 2001, that is, the end of steady hydrogen shell-burning. No supersoft X-rays are observed in the early decline phase because the photospheric radius of the WD is rather large and the photospheric temperature is relatively low. After the recurrent nova enters the plateau phase, the photospheric temperature of the WD increases to high enough to emit supersoft X-rays. During the massive wind phase, however, we do not expect supersoft X-rays because they are self-absorbed by the wind itself. U Sco was observed as a luminous supersoft X-ray source in the mid-plateau phase of the 1999 outburst just after the massive wind stopped (Kahabka et al. 1999; Hachisu et al. 2000a). Our analysis suggests that the massive wind stopped in early December 2000 and that supersoft X-rays are now very likely detectable until August 2001.

6. DISCUSSION

The calculated distance modulus of the 1917 outburst is about $(m-M)_B = 14.5$. Therefore, the distance to CI Aql is estimated to be 1.6 kpc for the reddening of $E(B-V) = 0.85$ and the absorption of $A_B = 3.5$ and $A_V = 2.7$. The apparent distance modulus of $(m-M)_V = 13.7$ from the 2000 outburst as shown in Figure 5 is also consistent with the distance of 1.6 kpc and $A_V = 2.7$.

On the other hand, we obtain an apparent distance modulus of $(m-M)_V = 12.86$ in the quiescent phase as shown in Figure 2, which corresponds to the distance of 1.1 kpc. This is not consistent with our estimation from the outburst light curves. To examine this difference, we check other observations and found that three others indicate $V \approx 16.2$ in quiescence, which is 0.7 mag darker than $V \approx 15.5$ in Figure 1 of Mennickent & Honeycutt (see Table 2 of Mennickent & Honeycutt 1995; Szkody & Howell 1992). The V magnitudes in their Figure 1 were obtained with a fully automated telescope and the errors in the zero point (formally 0.2 mag as in their text) could be larger than expected (private communication with Mennickent). If we adopt $V = 16.2$ in quiescence, then the distance modulus is $(m-M)_V = 13.56$ and the distance to CI Aql becomes $d = 1.5$ kpc, being consistent with the distance estimate from the outbursts. Thus, we determine the distance to CI Aql to be $d \sim 1.6$ kpc with $A_V = 2.7$.

The lacks of flickering and of Balmer emission lines in quiescence lead Mennickent & Honeycutt (1995) to conclude that CI Aql is not interacting at least at the present time. However, the inner part of the accretion disk cannot be seen from the Earth as easily understood from Figure 1. This is the reason for the lacks of emission lines and of flickering even when the system includes a mass-accreting WD. This is essentially the same situation as in U Sco (Schaefer 1990; Johnston & Kulkarni 1992; Schaefer & Ringwald 1995; Hachisu et al. 2000b).

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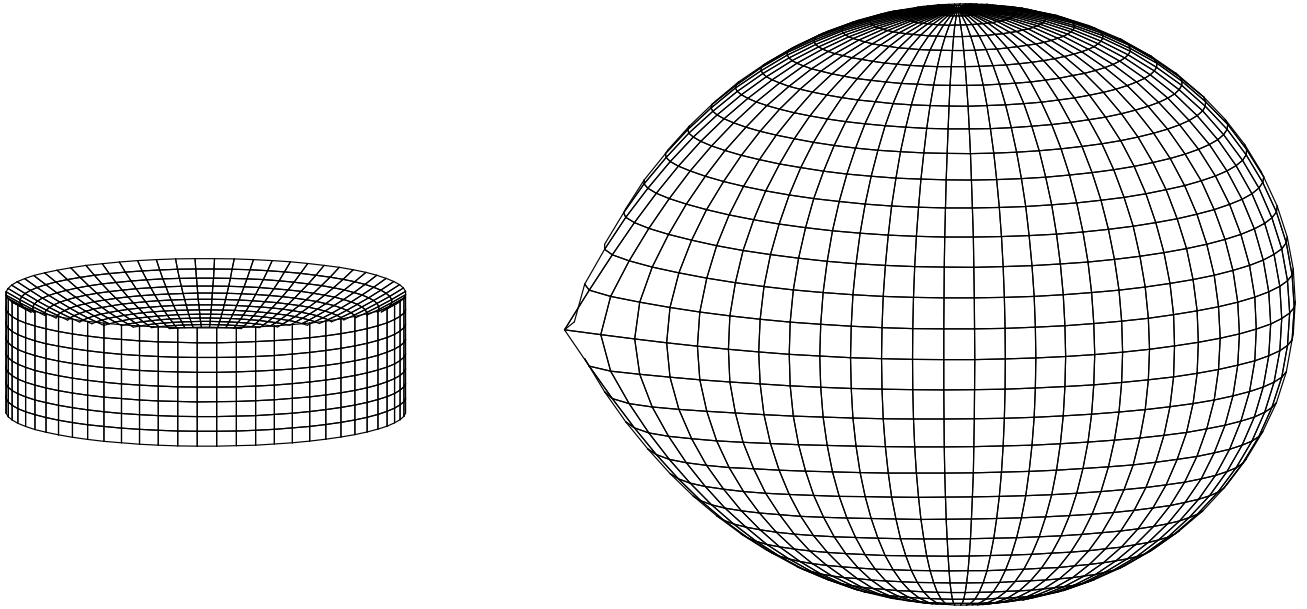


FIG. 1.— Configuration of our CI Aql model in quiescence. The cool component (*right*) is a slightly evolved MS ($1.5M_{\odot}$) filling up its inner critical Roche lobe. Only north and south polar areas of the cool component are irradiated by the hot component ($1.2 M_{\odot}$ WD, *left*). The hot component itself and the central part of the ACDK are not seen from the Earth because they are blocked by the flaring-up rim of the ACDK. Here the separation is $a = 4.25R_{\odot}$; the effective radii of the inner critical Roche lobes are $R_1^* = 1.53R_{\odot}$, and $R_2^* = R_2 = 1.69R_{\odot}$, for the primary WD and the secondary MS, respectively.

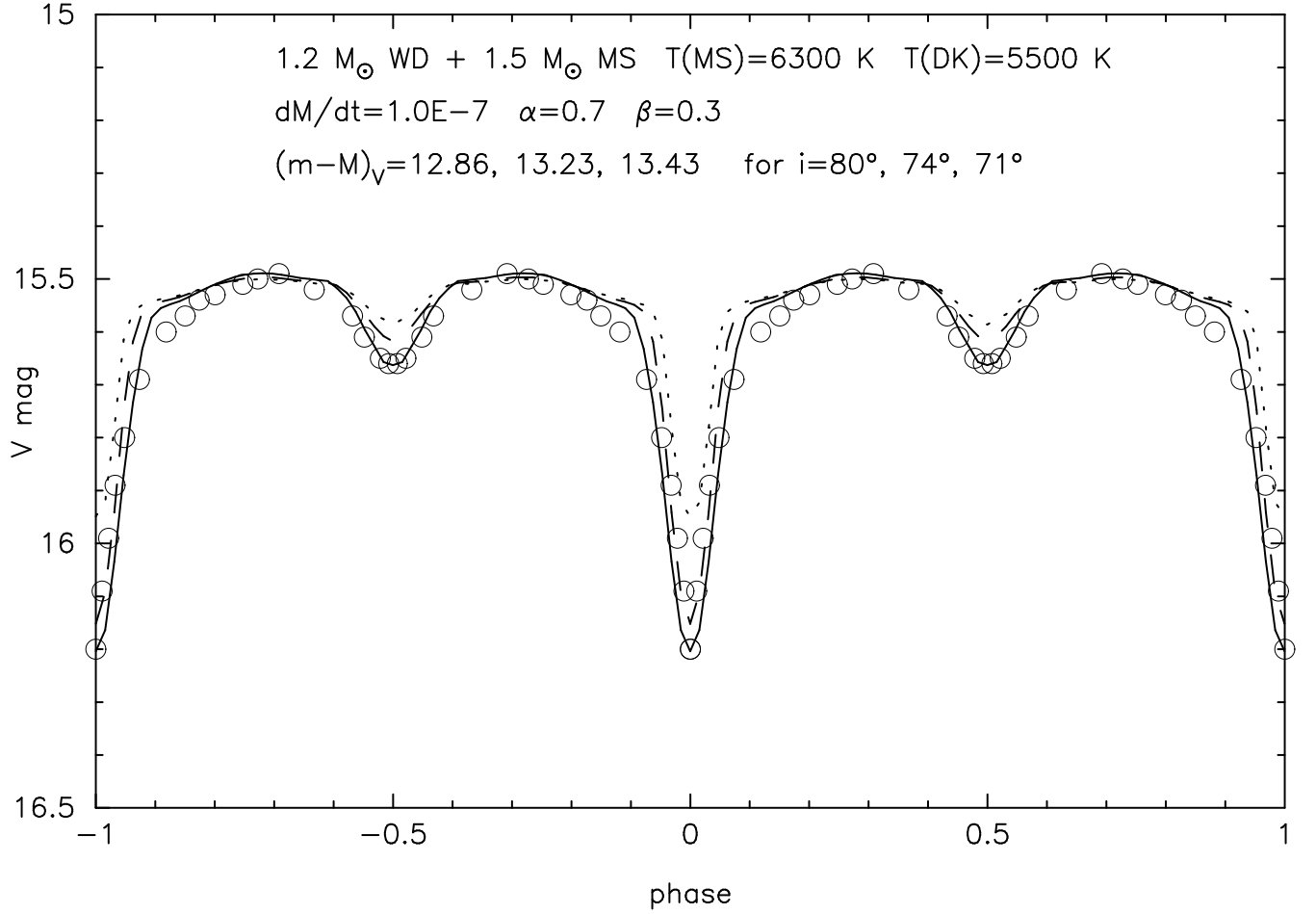


FIG. 2.— Calculated V light curves are plotted against the binary phase (two phases from -1.0 to 1.0) together with the smoothed observational points (open circles) taken from Mennickent & Honeycutt (1995). The model is a binary system of $1.2M_{\odot}$ WD + $1.5M_{\odot}$ MS. The other parameters are printed in the figure. Light curves are plotted for different three inclination angles, i.e., $i = 71^\circ$ (dotted), 74° (dashed), and 80° (solid).

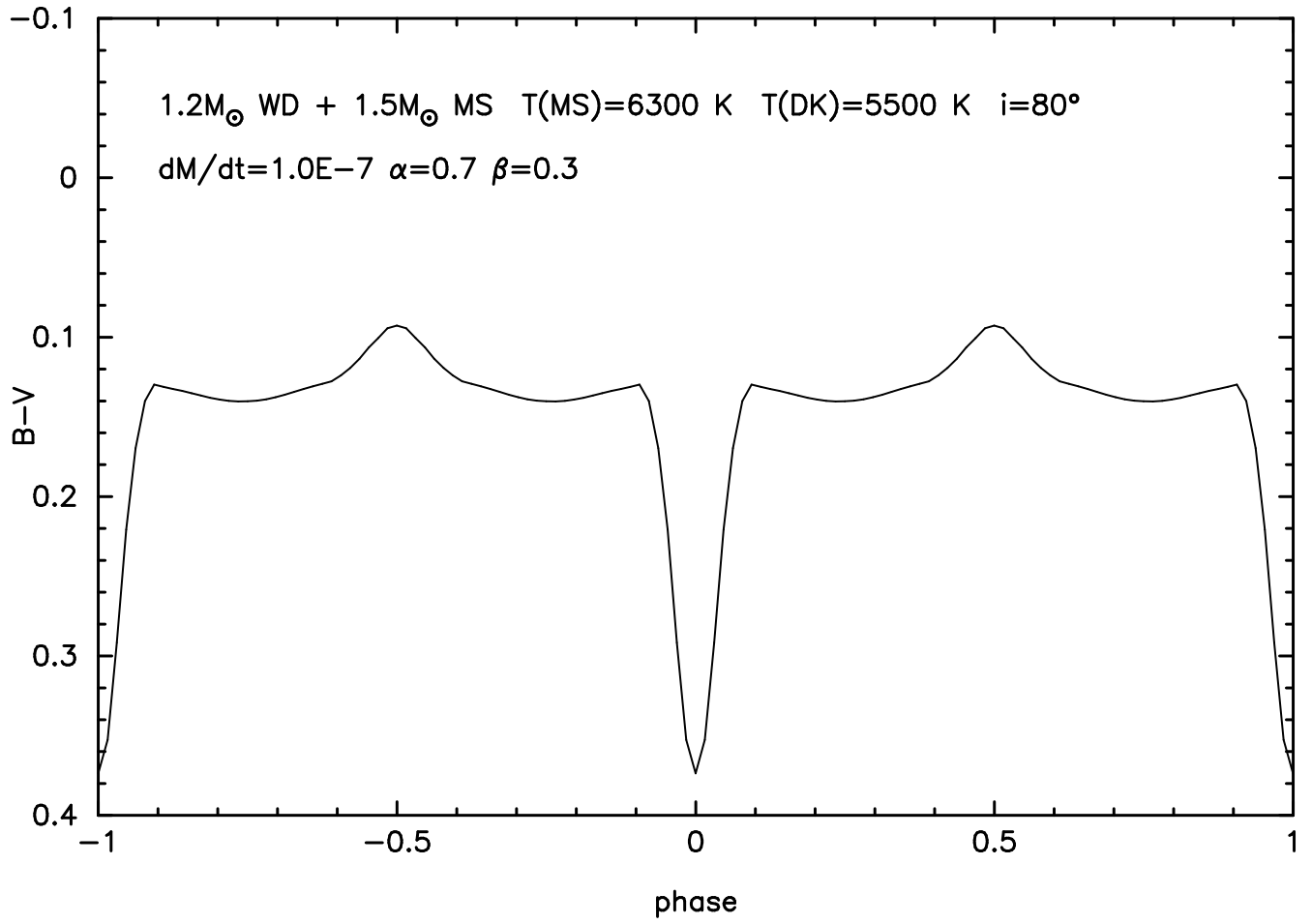


FIG. 3.— Calculated $B - V$ light curve against the binary phase for the inclination angle of $i = 80^{\circ}$.

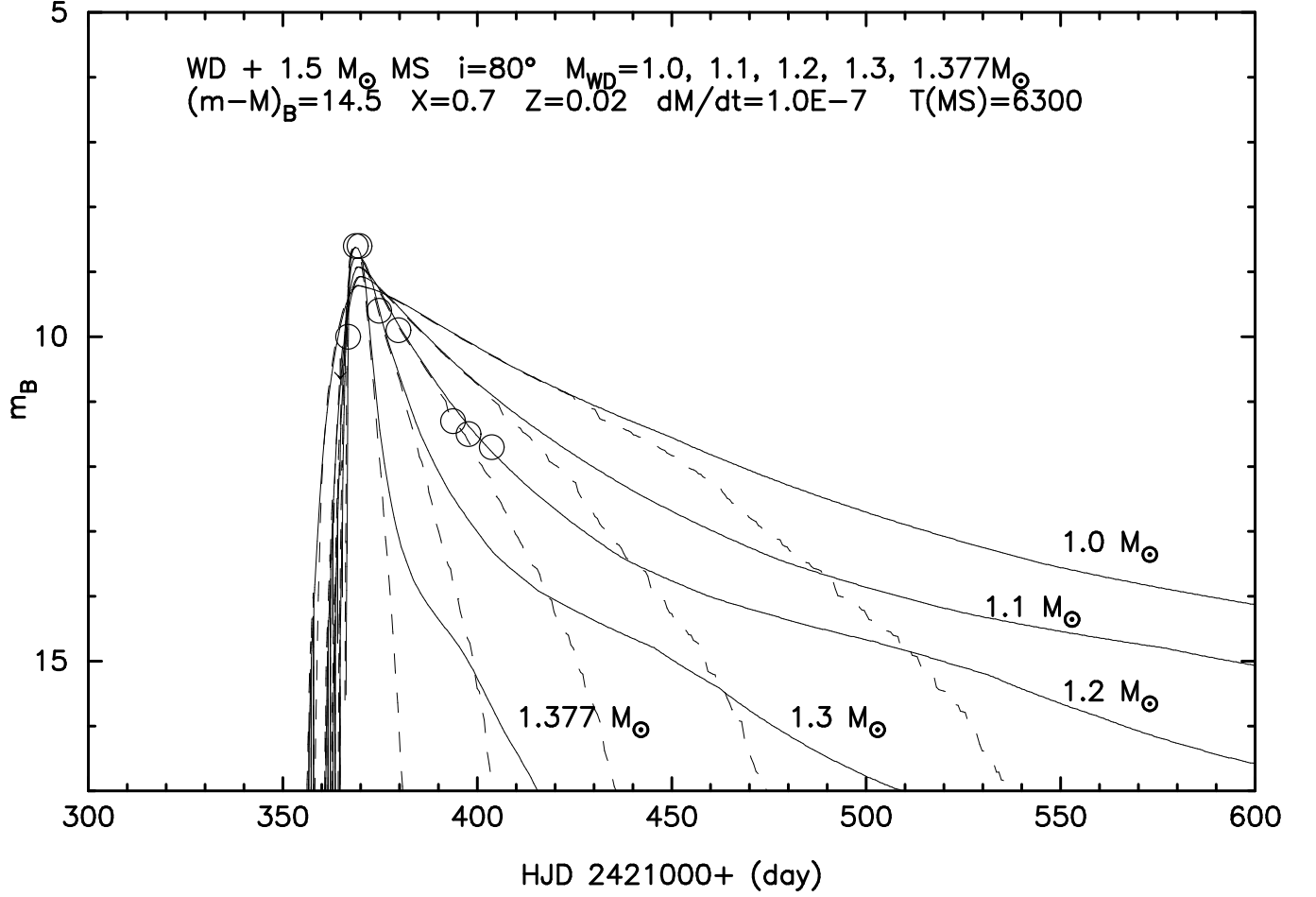


FIG. 4.— Calculated B light curves are plotted against time (HJD 2,421,000+) together with the observational points of the 1917 outburst. Open circles indicate observational points (taken from Williams 2000). The model consists of a bloated WD photosphere with no accretion disk and a non-irradiated MS companion. The hydrogen content of the WD envelope is assumed to be $X = 0.70$ for all models. The apparent distance modulus of $(m - M)_B = 14.5$ is assumed for all the WD masses. Solid lines indicate the light curves connecting the B light at the binary phase 0.5 (roughly the mean brightness) while dashed lines correspond to those connecting the B light at the binary phase 0.0 (mid-eclipse).

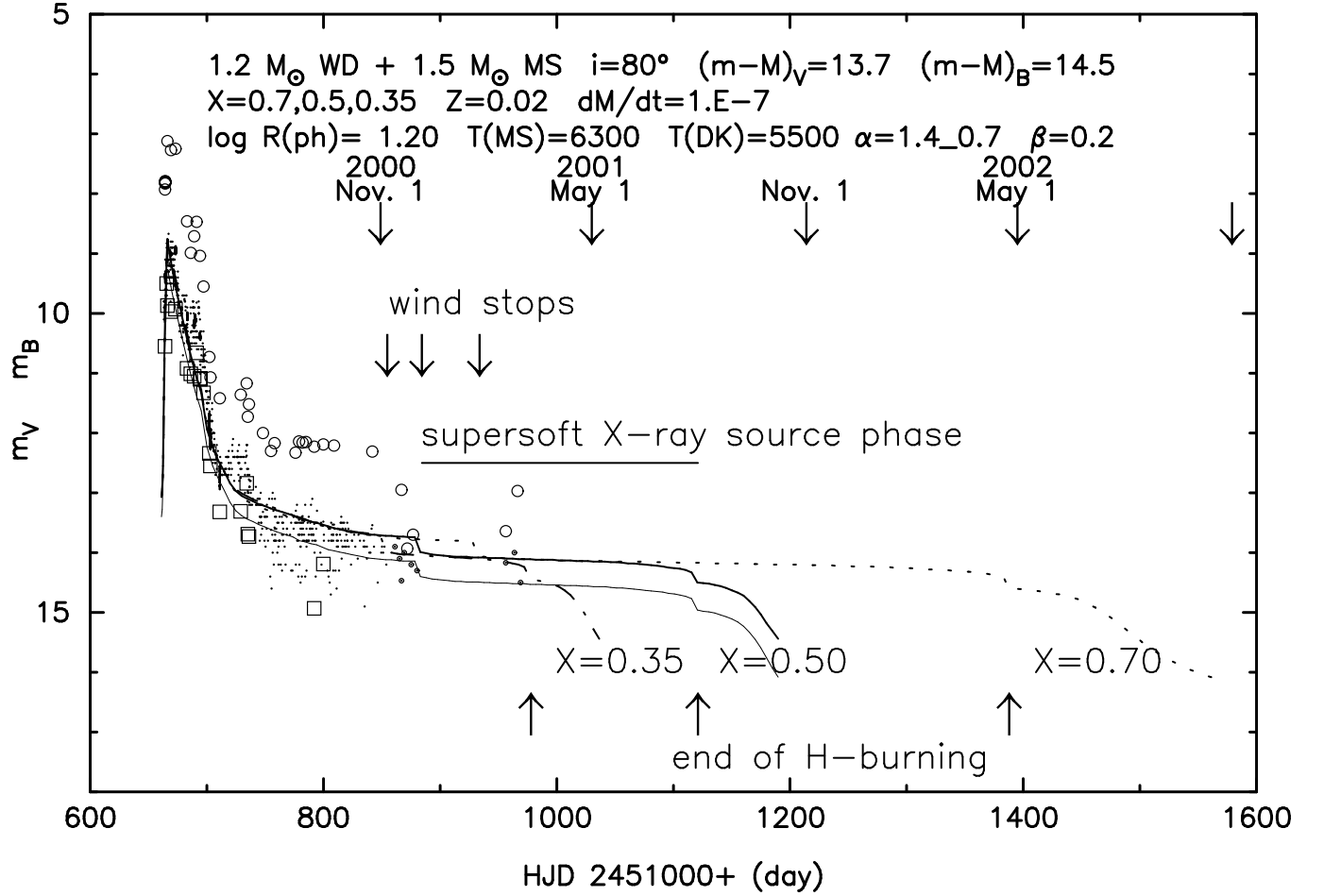


FIG. 5.— Calculated V and B light curves are plotted against time (HJD 2,451,000+) together with the observational points of the 2000 outburst. Small dots indicate observational V and visual magnitudes while open squares represent observational B magnitudes and open circles indicate observational I magnitudes (all taken from VSNET archives). Calculated V light curves are plotted for three different hydrogen contents of the WD envelope, $X = 0.70$ (thick dotted), $X = 0.50$ (thick solid), and $X = 0.35$ (thick dot-dashed). Thin solid line indicates B -magnitude of $X = 0.50$ case. Each light curve connects the brightness at the binary phase 0.5 (roughly the mean brightness). The apparent distance moduli of $(m - M)_V = 13.7$ and $(m - M)_B = 14.5$ are obtained by fitting.